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Efficient generation of blue light by intracavity frequency doubling of a cw Nd:YAG laser with LBO

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Abstract

We report on the efficient room-temperature operation of $^4F_{3/2}$–$^4I_{9/2}$ transition in a diode pumped Nd:YAG laser operating at 946 nm. An output power of 5.1 W and a slope efficiency of 23.6% at 946 nm have been obtained. Different LBO crystals of length $3\times3\times10\,mm^3$, $3\times3\times15\,mm^3$, $3\times3\times18\,mm^3$ were selected as frequency doubling material for comparison. A maximum single-ended output power of 1.3 W at 473 nm was achieved by frequency doubling with an optical conversion efficiency of 5%. When the Nd:YAG rod was replaced by the one with high reflectivity coating at 473 nm on the pump side, the output power of blue light was almost twice that without high reflectivity coating for 473 nm at the same pump power level. Moreover, the theoretical optimum length of LBO crystal for intracavity frequency doubling was discussed, and the experimental results made a good agreement with it.

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Keywords: Blue light; Nd:YAG; Intracavity doubling

1. Introduction

Compact high-power blue lasers are in demand for color display, underwater communication, Lidar and high-resolution printing. The argon-ion (Ar^{3+}) or HeCd lasers are among the sources in blue spectral region. However, they suffer from low efficiency, short lifetimes, and excessive optical-noise levels. By frequency doubling a diode-pumped all-solid-state Nd-ion-doped laser at the quasi-three-level $^4F_{3/2}$–$^4I_{9/2}$ transition, one can obtain compact, stable and high-power blue laser. From the large number of Nd-doped materials, Nd:YAG laser was the most important source because of its high gain and good thermal and mechanical properties [1–6].

The choice of nonlinear materials for intracavity frequency doubling of the high power cw Nd-ion-doped lasers was BBO, BiBO, $LiNbO_3$, LBO, PPKTP and PPLN [3–8]. For frequency doubling of cw lasers, a high nonlinear coefficient, small absorption losses and good optical quality were the determining factors for the selection of a particular crystal. LBO was a negative biaxial crystal, which possesses a relatively high optical-damage threshold, a moderate nonlinear optical coefficient and small walk-off angle and large spectral- and angular acceptance bandwidth. These properties, along with its mechanical hardness, chemical stability and nonhygroscopicity, make LBO an attractive material for certain nonlinear optical processes [5,9,11]. Recently, as much as 2.2 and 1.5 W of 473 nm radiation have been obtained, respectively, with a five-element folded cavity through intracavity frequency doubling with nonlinear crystal LBO [9,11].

In our experiments, we selected three LBO with different length (10, 15 and 18 mm) as frequency doubling crystals for comparison. As much as 1.3 W of single-ended blue output power has been generated through intracavity frequency doubling of Nd:YAG laser operation at $^4F_{3/2}$–$^4I_{9/2}$ transition at 946 nm. The whole cavity length was only 45 mm. To the best of our knowledge, for such a simple and compact linear cavity, it was the highest output

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power from a diode-pumped cw Nd:YAG laser in the blue spectral region. Furthermore, the theoretical optimum length of LBO crystal used as intracavity frequency doubling has been discussed. The experimental results made a good agreement with it.

2. Fundamental-wave laser

The experimental set-up was given in Fig. 1. The pump source was a high-brightness fiber-coupled diode laser at 808 nm with core diameter of 400 μm and a NA of 0.22. The maximum pump power reaching the laser rod after the coupling mirrors was 26 W. A composite laser rod, two sides of a 3-mm thick Nd:YAG crystal were diffusion bonded with 3-mm thick undoped YAG end caps, was used as the gain medium. Because the undoped region was transparent to the pump radiation, there was no thermal load generated in the end caps, and the diffusion bond provides heat flow from the doped to the undoped region. Therefore, a large temperature reduction of the gain medium can be achieved. It was essential for this quasi-three-level laser at 946 nm. The length of the Nd:YAG crystal was 3 mm, to balance the needs of decreasing the reabsorption losses and absorbing reasonable fraction of the pump power. The diameter of the crystal was 3 mm to achieve efficient heat transfer. The laser rod was cooled directly with water ($T = 14\,^{\circ}C$), which leads to good heat removal. The pump facet of the laser rod was coated with high transmission (HT) for the pump light at 808 nm, high reflection (HR) at 946 nm. High transmission at 1064 and 1320 nm was also specified to prevent oscillating on the strong four-level transitions in Nd^{3+}. The other side of the rod was coated with antireflection (AR) at 946, 1064 and 1320 nm.

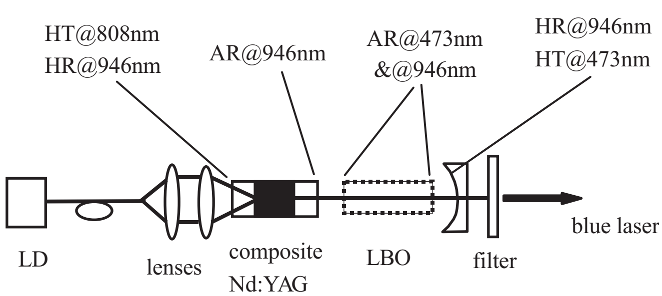

Fig. 1. Experimental setup of intracavity frequency doubled Nd:YAG laser.

The laser experiments on the ground-state transition at 946 nm were carried out without the nonlinear crystal LBO in the cavity. Firstly, a concave mirror with curvature radius of 100 mm and 2% transmission at 946 nm was used as output coupler. The laser threshold was 4.8 W. A maximum output power of 4 W was generated at incident pump power of 26 W. When the output mirror was replaced by the one with the curvature radius of 100 mm and 3.7% transmission, the output power was enhanced to 4.2 W. Another concave output coupler with a transmission of 5% and curvature radius of 50 mm gave a slightly increased power value of 5 W corresponding to a slope efficiency of 23.6%. The output power of 946 nm as a function of the pump power was shown in Fig. 2. The stability of all the output powers were better than 1% and no degradation was observed during the operation of 2 h.

3. Frequency doubling

3.1. Optimum length of LBO crystal

If Maxwell's equations are solved for a coupled fundamental and second-harmonic wave propagating in a

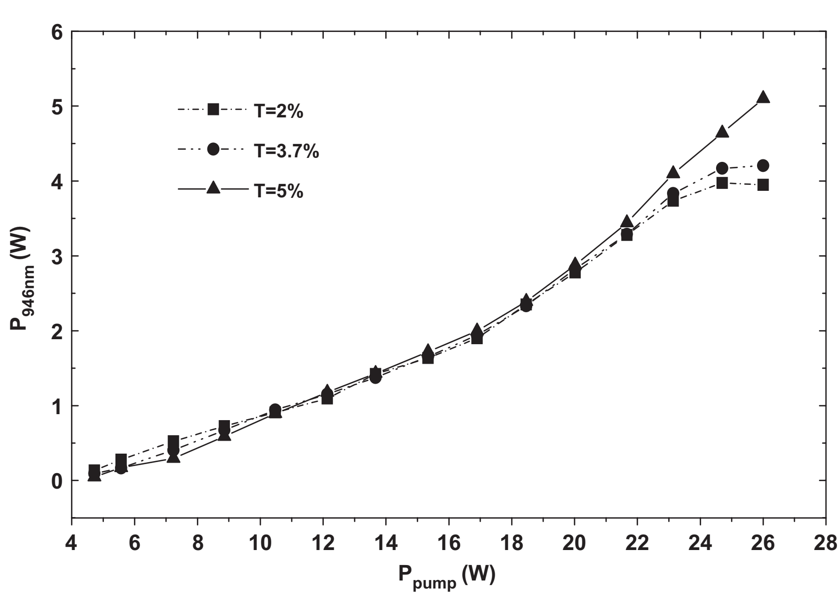

Fig. 2. Output powers at 946 nm versus incident pump powers with different output couplers.

nonlinear medium, then the ratio of the power at the second-harmonic frequency to the incident power at the fundamental wave is given by [12]

$$\frac{P_{2\omega}}{P_{\omega}} = \tanh^2\left[lK^{1/2}(\frac{P_{\omega}}{A})^{1/2}\frac{\sin(\Delta kl/2)}{\Delta kl/2}\right], \quad (1)$$

where

$$K = 2\eta^3\omega^2 d_{\rm eff}^2, \quad (2)$$

l is the length of the nonlinear crystal, A is the area of the fundamental beam, η is the plane-wave impedance, ω is the frequency of the fundamental beam, $d_{\rm eff}$ is the effective nonlinear coefficient, and Δk is the phase mismatch between the polarization and the em wave for collinear beams.

For low conversion efficiencies, Eq. (1) would be approximated by

$$\frac{P_{2\omega}}{P_{\omega}} = l^2 K\frac{P_{\omega}}{A}\frac{\sin^2(\Delta kl/2)}{(\Delta kl/2)^2}. \quad (3)$$

Just as the analysis in Ref. [13], the steady-state condition for intracavity frequency doubling can be determined if the round-trip-saturated gain of the laser was equated to the sum of the linear and nonlinear losses

$$\frac{2g_0 l^*}{1+I/I_{\rm s}} = L + K'I, \quad (4)$$

where g_0 is the unsaturated gain coefficient, l^* is the length of the laser medium, L is all the linear losses occurring at the fundamental frequency, I is the power density in the laser rod, and $I_{\rm s}$ is the saturation power density of the active material. For the quasi-three-level laser of Nd:YAG at $^4F_{3/2}$–$^4I_{9/2}$ transition at 946 nm, $I_{\rm s}$ is defined by [14]

$$I_{\rm s} = \frac{hv}{(f_a + f_b)\sigma\tau}, \quad (5)$$

where v is the frequency of the laser $\omega = 2\pi v$, f_a is the fraction of the $^4I_{9/2}$ population that resides in the Stark component used as the lower laser level, f_b is the fraction of the $^4F_{3/2}$ population that resides in the Stark component used as the upper laser level. σ is the stimulated emission cross section for the quasi-three-level laser transition, and τ is the lifetime of the upper state.

In (4), $K'I$ is the nonlinear loss caused by frequency doubling, and the nonlinear coupling factor K' is defined by [16]

$$I(2\omega) = K'I^2(\omega), \quad (6)$$

which is related to K in (2). That is

$$K' = \kappa l^2 K, \quad (7)$$

where κ is the ratio of the power densities in the laser rod to that in nonlinear crystal; that is, $\kappa = I_{\rm crystal}/I_{\rm rod}$.

From the theoretical treatment of intracavity doubling, it follows that a maximum value of second-harmonic power is found when

$$K' = \frac{L}{I_{\rm s}}. \quad (8)$$

From the relation above, it is shown that the magnitude of the nonlinearity required for optimum second-harmonic production is proportional to the loss, inversely proportional to the saturation density, and independent of the gain. Therefore, for a given loss, optimum coupling is achieved for all power levels. From (2) and (5) combing with (7) and (8), the optimum length of the nonlinear crystal can be obtained

$$l = \left(\frac{fL\sigma\tau\lambda}{2hc\eta^3\omega^2 d_{\rm eff}^2\kappa}\right)^{1/2}. \quad (9)$$

3.2. Frequency doubling experiments

For efficient frequency doubling of cw Nd:YAG laser at 946 nm, the optimum length of LBO crystal was determined according to the theory we have presented. About 14-mm-long LBO should be selected as intracavity frequency doubling crystal. The following parameters have been used in the calculations: $f_a = 0.0074$, $f_b = 0.6$, $\sigma = 5.1\times10^{-20}\,{\rm cm}^2$ [15], $\tau = 230\,\mu{\rm s}$, $d_{\rm eff} = 0.81\times10^{-12}$ m/V [7], $n_0 = 1.56$ [16], and $L = 0.03$.

At first, the 15-mm-long LBO crystal was inserted into the cavity and adjusted carefully to yield good doubling efficiency in the crystals. The nonlinear crystal LBO was cut for type I phase matching at 946 nm ($\Theta = 90^\circ$, $\Phi = 19.37^\circ$) and was coated for antireflection (AR) at 473 and 946 nm to reduce the reflection losses in the cavity. It was wrapped with indium foil for reliable heat transfer and mounted in a copper block, which was fixed on a thermoelectric cooler for an active temperature control with stability of $\pm0.1\,^\circ$C. The output mirror was replaced by the one with curvature radius of 100 mm, which was coated with high reflection at 946 nm ($R>99.8\%$) and high transmission at 473 nm ($T>90\%$) and 1.06 μm ($T>80\%$). The 1.3 W of single-ended blue output power at 473 nm was achieved with optical conversion efficiencies of 5%. Then a 10-mm LBO crystal replaced the 15 mm one. The maximum blue output power was 0.9 W. When another LBO crystal with 18-mm-long was inserted into the cavity instead, we found that the output power decreased apparently, and only 0.65 W at 473 nm was generated. The thresholds of these lasers were approximately equal. The value of the threshold was about 3 W. The output powers of blue lasers at 473 nm for different LBO crystal length as a function of the incident pump power were shown in Fig. 3. The output powers were all measured at the optimum LBO temperature of 23 °C, which maximized the blue output power at a given incident pump power [10]. From the results of our experiments, it was shown that the 15-mm-long LBO crystal was the optimum choice for the

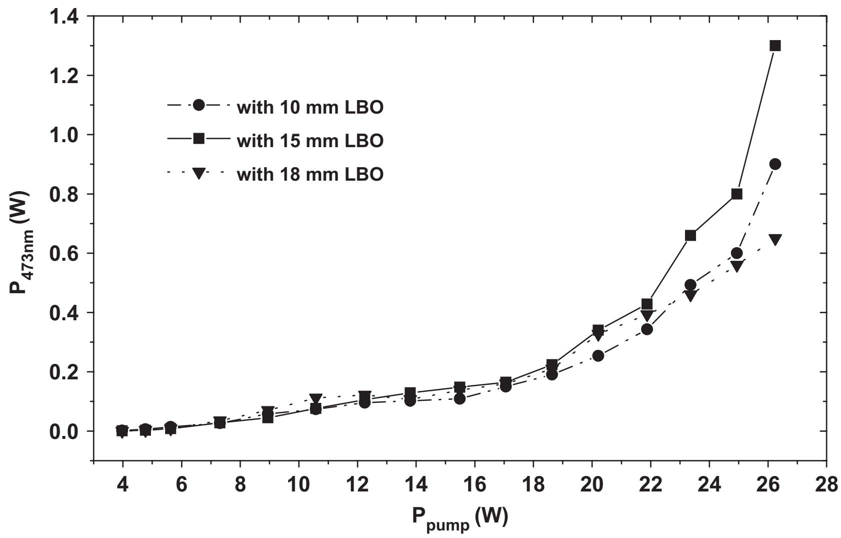

Fig. 3. Single-ended output powers at 473 nm versus incident pump powers with different LBO crystals in length: 10, 15, and 18 mm.

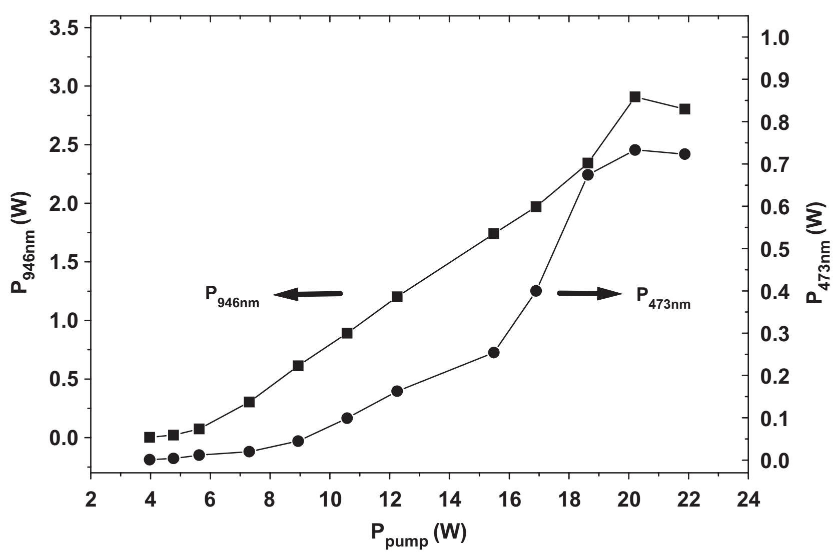

Fig. 4. Output powers at 946 and 473 nm with high reflectivity coating at 473 nm on the pumping side of the composite laser rod by using 15-mm-long LBO crystal.

intracavity frequency doubling of the linear cavity configuration we have employed. The experiment resulted in a good agreement with the theoretical calculation.

Since the pump side of the Nd:YAG crystal was not coated for high reflectivity at 473 nm, there was also strong blue light emitted from this side, which was almost as strong as that from the output side [3]. In order to obtain all the harmonic power in a single output beam, the laser rod was substituted for one coated for high reflectivity at 473 nm on the pump side to reflect one of the beams back in the same direction as the other. Therefore, a $3 \times 3 \times 9\,\text{mm}^3$ composite Nd:YAG laser rod, a $3 \times 3 \times 3\,\text{mm}^3$ Nd:YAG diffusion bonded with two same size undoped YAG crystal, was employed. Firstly, we measured the output powers at 946 nm without LBO crystal in the cavity and the results were shown in Fig. 4. We found that the output power at 946 nm began decreasing when the pump power was increased to about 20 W. It was mainly because the cubic laser rod provides poorer heat transfer than the cylindrical one, which brought out serious thermal effect. With 15-mm-long LBO crystal in the cavity for frequency doubling, the blue output power at 473 nm also began decreasing as the pump power was higher than 20 W just as shown in Fig. 4. However, at the same pump power, which was lower than 20 W, the blue output power was almost doubled compared to that without high reflectivity coating for 473 nm at the pump side. Therefore, when the pump side of the Nd:YAG was coated with high reflectivity at 473 nm, the output power of the second harmonic would be enhanced largely.

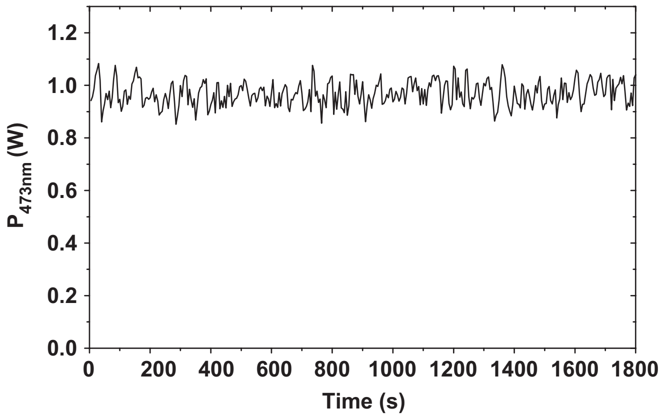

Fig. 5. Temporal behaviors over 30 min of blue output at single-ended output power of 1.1 W.

However, it needs another laser rod, which is not available at present.

The stability testing of the blue laser was carried out by monitoring the output power with power-meter. When the 15-mm-long LBO was used in the cavity, the stability of blue output was measured and the temporal behavior in 30 min was shown in Fig. 5. The output noise was 3.7% at the average output power of 1.1 W. There was no degradation of the output power at high levels in 2 h of operation. Moreover, abrupt changes [10] in output power were not observed. It possibly results from the optimum structure of the cavity and the suitable length of LBO crystal. The stability at lower output power was much better than that at high output power.

4. Conclusion

In conclusion, we have demonstrated a diode-pumped cw Nd:YAG laser operating at 946 nm for an output power of 5 W and a slope efficiency of 23.6% at incident pump power of 26 W. By intracavity frequency doubling with LBO crystal, single-ended blue output powers of 1.3 W at 473 nm was generated. The stability of 3.7% at the average output power of 1.1 W was investigated in 2 h of operation and no degradation was observed. When the laser rod was replaced by the one with a high reflectivity coating at 473 nm on the pump side, the total output power of blue light was enhanced largely at the same pump power.

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